SAPPHIRE FIBER INTERFEROMETER

FOR MICRODISPLACEMENT MEASUREMENTS AT HIGH TEMPERATURE

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INTRODUCTION

Standard silica-based optical fibers are currently being used in a wide variety of sensing applications where the operating temperatures do not exceed 500°C. In a number of applications where higher temperatures are encountered and harsh environments are unavoidable, it is imperative that both optical waveguides and optical waveguide coatings fabricated from materials other than silica be considered. Sapphire is one such candidate material that possesses reasonable optical propagation properties in both fiber and rod form, and can potentially perform without significant degradation under harsh conditions, including temperatures up to 2000°C.

In experiments reported thus far, unclad sapphire rods have been used only in intensity-based sensors because of their large numerical apertures. Numerical apertures of silica-clad sapphire rods have been found to vary from 0.55 to 0.83 but their available core diameters are not sufficiently small to allow single-mode operation at optical wavelengths. Since phase-modulated interferometric sensors which require single-mode optical fiber waveguides are many times more sensitive than their multimode counterparts, methods of fabricating single-mode sapphire fibers are being investigated.

In this paper, we report the use of a short-length, multimode sapphire rod as an extension to a conventional Michelson interferometric configuration, but operated as a low-finesse Fabry-Perot cavity-based sensor element. We demonstrate the performance of such a device as an interferometric sensor, where the interference between the reflections from the sapphire-air interface and an air-metallic surface is observed for microdisplacements of the metallic surface which is placed close to, but not touching the sapphire rod endface. We describe in detail the fabrication procedure and present results obtained from the detection of surface acoustic waves.

The development of advanced high temperature materials, and the increasing demand for the control of advanced high temperature combustion and industrial processes, require sensor instrumentation which can perform reliably in high temperature environments. During the past ten years, optical fiber instrumentation has been applied to a wide variety of materials and process instrumentation situations. Optical fiber sensor methods offer the advantages of multiplexed and multimeasurand operation, combined with the avoidance of electromagnetic interference effects and ground loop networking problems [1].

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Conventional communication grade optical fiber waveguides are made of silica, are typically 125 to 140 microns in diameter, and are coated with acrylate polymers which perform well over the full range of extended ambient environmental temperatures, but which degrade at temperatures much above 150°C. Above those temperatures, higher temperature polymer coatings are required. These are typically polyimide-based, and allow operation to the 400°C to 500°C range. Applications at still higher temperatures require the use of metal or ceramic-coated silica fibers. Gold-coated silica fibers, for example, perform well up to the temperatures where 1) the dopants in conventional silica fibers begin to migrate and thus adversely affect both waveguide guidance and attenuation properties, and 2) the doped silica begins to soften [2]. These temperatures are approximately 800-900°C.

At still higher temperatures, the options are limited. For selected measurements, platinum gauges are alternatives, although typically they have the disadvantages of electromagnetic interference, ground loop instrumentation difficulties, and single-measurand capability. Sapphire-fiber/rod-based interferometric sensors offer an alternative technology which avoids some of these intrinsic disadvantages while offering competitive sensitivity and resolution performance.

SAPPHIRE FIBER WAVEGUIDES

Optical quality sapphire rods can be grown as single crystals using several standard methods [3]. Outer diameters of typical commercially available sapphire rod waveguides vary between fifty and several hundred microns, with lengths up to several tens or hundreds of centimeters. Such rods do not have outer cladding regions of lower index of refraction than the core material the way that conventional silica fiber waveguides do. Such cladding layers normally are required to effectively confine the propagating optical power within the waveguide, and to thus limit both optical attenuation and cross-coupling which may occur between adjacent waveguides, as well as into the surrounding environment.

Such sapphire rods also do not have external coating layers designed to protect the sapphire from the surrounding environment. These types of protective coatings have been shown to be of special importance in applications involving exposure to harsh chemical contaminants at high temperatures [4]. Coating layer materials are also important for the transfer of strain and temperature from the material to be evaluated to the sapphire fiber sensor element. For high temperature measurement applications, the coefficient of thermal expansion mismatch between the sapphire fiber element and the host material may lead to a loss of interfacial contact, and a resulting discontinuity in heat flow and strain at the boundary. Alternatives for the possible solution of this problem, including multi-layer geometries of different coating materials, have been suggested [5].

OPTICAL FIBER SENSORS USING SAPPHIRE FIBER ROD WAVEGUIDES

Since single mode optical fibers are currently not available, we have implemented fiber interferometers using bulk sapphire rods. Figure 1 shows the geometry of a particular implementation. Here we use a five millimeter diameter sapphire rod as a bulk optics component. A graded index lens couples light from an input single mode silica optical fiber into the rod and produces a collimated optical beam with a waist size on the order of one millimeter. Thus, the optical beam which propagates down the length of the sapphire rod and back approximately at the center of the rod does not substantially interact with the outer surface of the rod and hence the external physical environment. For ease of assembly, the lens, the input fiber and the rod are mounted in a conventional optical fiber connector ferrule and for durability the components have been attached together using low temperature epoxy-based adhesives. The temperature limitations of this design are imposed by the low temperature epoxy as well as by the higher temperatures at which the dopants in the lens migrate, thus altering the index of refraction profile of the lens and degrading its collimation properties.

The interferometric geometry shown in Figure 1 has been used to measure the displacement of a metallic surface at high temperature in an oven. As shown in Figure 2, the space between

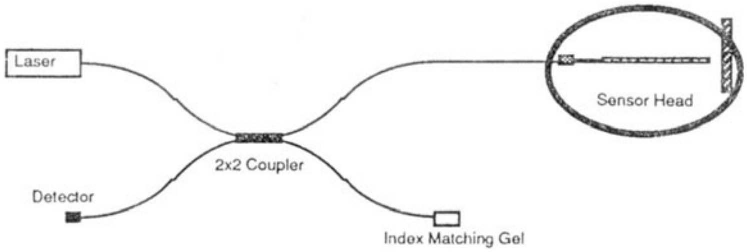

Figure 1. Sapphire Fiber Interferometer Geometry.

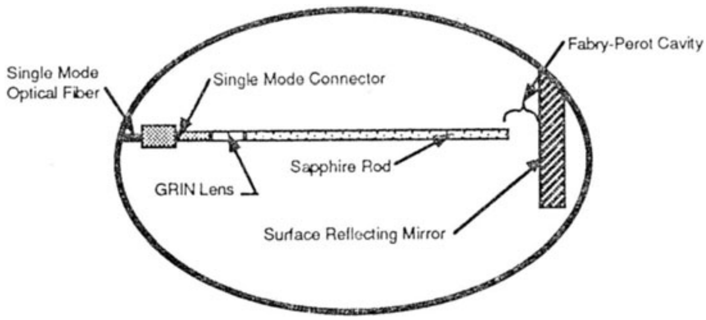

Figure 2. Detail of Sapphire Fiber Sensor Head.

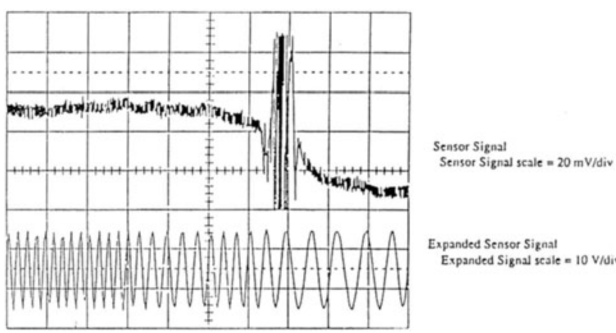

Figure 3. Sappire Interferometer Output Fringes Corresponding to Surface Displacement (2s/div).

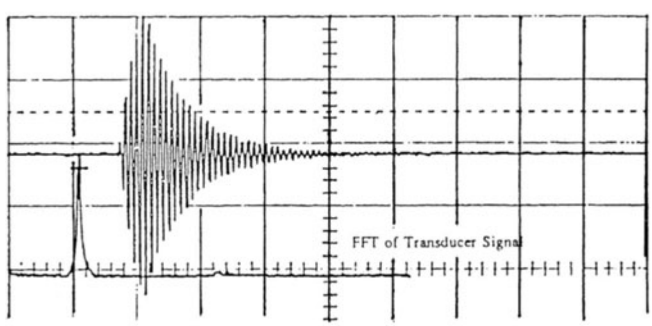

Figure 4. 150kHz SAW Pulse on 1100°C Metal Surface

the end of the sapphire rod and the metallic surface forms a low finesse Fabry-Perot cavity the length of which changes as the surface is displaced. The back reflected interference signal travels along the sapphire rod, back through the lens and into the single mode fiber through which it is coupled to the in-line fused biconical tapered coupler to an optical detector. The output of the detector is proportional to the intensity of the interference pattern generated by the Fabry-Perot etalon. Standard techniques for the determination of displacement, either by counting successive interference fringes for relatively large displacements, or by monitoring intensity modulation within one optical fringe for relatively small displacements, may then be used to determine displacement as a function of time.

Figure 3 shows surface displacements measured at room temperature. Here the interferometer housing was displaced mechanically by means of a micropositioner. The top trace shows a number of fringes corresponding to a 0.1 millimeter total displacement; the bottom trace is an expanded view of part of that multifringe signal which clearly shows that the effect being measured is a sinusoidal interference effect.

The interferometer has also been used to monitor surface acoustic waves on a reflective surface, also at room temperature. The geometry of the setup is similar to that shown in Figure 3 above, except that a piezoelectric transducer source is mounted on the surface of the material to generate surface acoustic waves in the vicinity where the sapphire rod effectively observes the surface displacements. Figure 4 shows the output data obtained for a 150 kilohertz acoustic wave propagating on the reflective material surface. Here, an averaging effect is observed due to the relative size of the probing optical beam and the acoustic wavelength of the surface wave [6].

SUMMARY

We have demonstrated the operation of a sapphire optical fiber interferometer which can be used to make measurements at high temperatures. Both surface displacements and ultrasonic wave propagation have been measured using this simple interferometer, and extensions to other material properties seem feasible due to these preliminary experimental results.

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